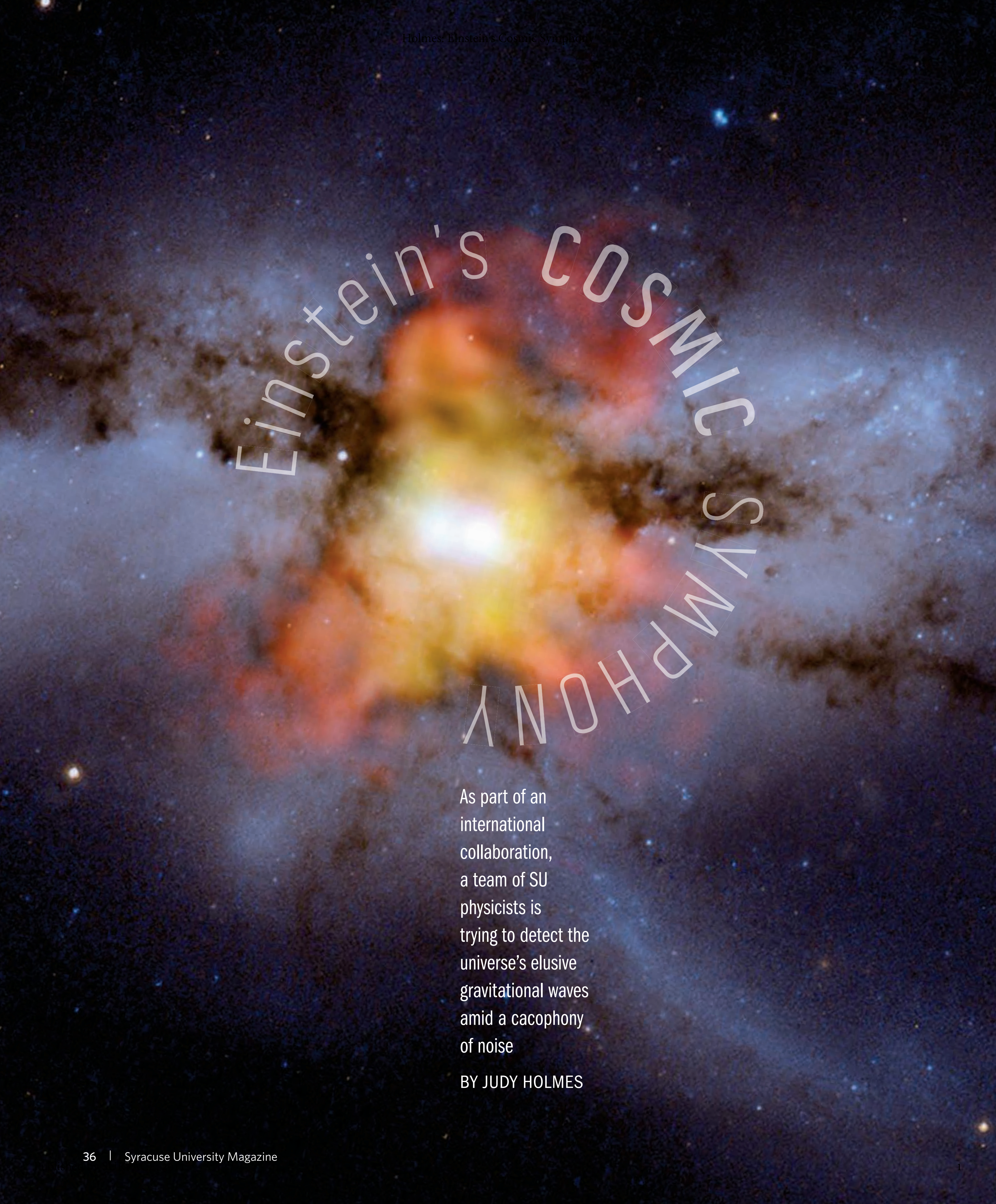
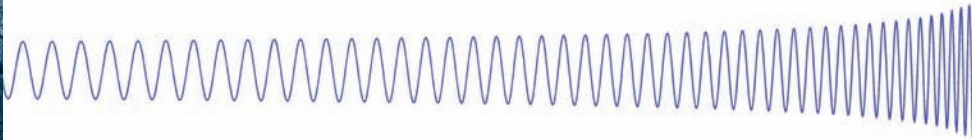


Einstein's COSMIC SYMPHONY

As part of an international collaboration, a team of SU physicists is trying to detect the universe's elusive gravitational waves amid a cacophony of noise

BY JUDY HOLMES

The LIGO Livingston Observatory in Louisiana was built to help scientists detect gravitational waves.



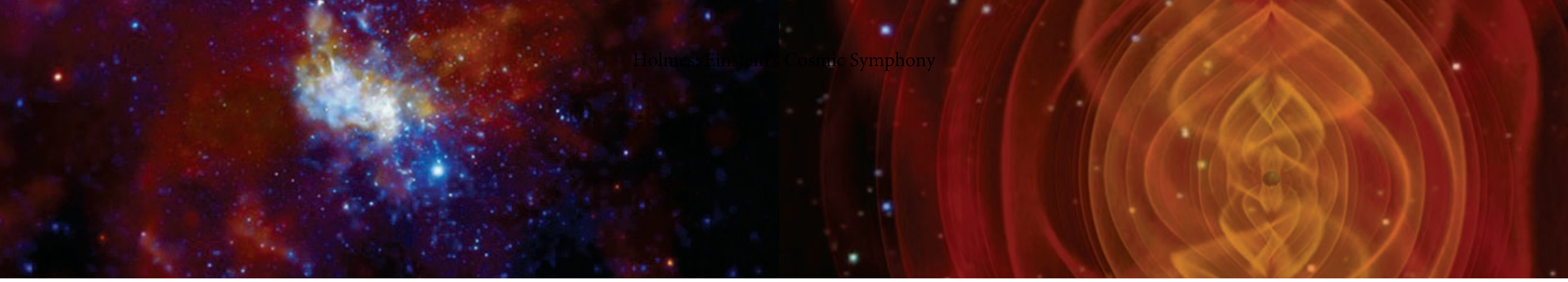
SOMEWHERE in the vast expanses of the universe, two spinning black holes are locked in a death spiral, pulled together by gravity. They collide. The violent confrontation produces ripples—gravitational waves, which herald news of the event at the speed of light across space and time. These are Einstein's Messengers.

Albert Einstein predicted the existence of gravitational waves in 1916 in his theory of general relativity; it took more than 80 years for scientists to invent ways to detect them. Like radio waves, which need to be decoded and amplified by a radio before music can be heard, gravitational waves need to be decoded by instruments that can distinguish the music from the noise. Scientists believe this cosmic music is encoded with information about the celestial bodies—colliding black holes, neutron stars, and exploding stars—that generate the waves, as well as with clues that may reveal the fundamental nature of gravity, and perhaps, the origin of the universe.

Scientists in the College of Arts and Sciences are among a select group of gravitational-wave researchers in the country who are leading efforts to decode Einstein's symphony. The SU group is part of a worldwide coalition of scientists called the Laser Interferometer Gravitational Wave Observatory Scientific Collaboration, or LIGO as it's known. In partnership with the National Science Foundation (NSF), the consortium—led by the Massachusetts Institute of Technology (MIT) and the California Institute of Technology (Caltech)—built facilities in Hanford, Washington, and Livingston, Louisiana, to search for the elusive waves. Commissioned in 2001, the LIGO observatories were operational until October 2010, when the instruments were dismantled to make way for Advanced LIGO, the next generation of the project (see page 39). The observatories are expected to be fully operational again in 2015.

Through its participation in the LIGO Scientific Collaboration, the SU group has garnered almost $8 million in NSF funding for the University since 1991. That's when Peter Saulson arrived at SU and established one of the first, NSF-funded, LIGO-related research labs outside of Caltech and MIT. Saulson, the Martin A. Pomerantz '37 Professor of Physics in the College of Arts and Sciences, trained under the best. Fresh out of Princeton with a newly minted Ph.D., he went to MIT in 1981 and spent eight years working with Rainer Weiss, a giant in the gravitational-wave field who developed the concept for LIGO's core technology—the laser interferometer, a device designed to

Image on facing page courtesy of NASA; top image courtesy of LIGO Laboratory



detect gravitational waves passing across Earth on their cosmic journey. "It was an act of intellectual courage for the College of Arts and Sciences to hire me," Saulson says. "There had been no history of NSF funding for LIGO outside the core groups." Saulson was the lead scientist for the LIGO Livingston Observatory in 2000, ensuring the instrument was constructed properly and performed well, and served as the scientific spokesperson for the LIGO collaboration between 2003 and 2007. In addition, Saulson did early research at SU that played a key role in improving the glass mirrors—key components in the interferometer—that will be installed in Advanced LIGO.

Five years ago, Professor Duncan Brown joined the SU physics department. As a graduate student at the University of Wisconsin-Milwaukee (UW-M), Brown wrote a major piece of the gravitational-wave search software used by LIGO. He subsequently spent three years working with Caltech's Kip Thorne who, alongside Weiss, is a key player in gravitational-wave research and in the LIGO collaboration. Brown, an NSF CAREER award recipient and Cottrell Scholar, is the principal investigator in a project to build a LIGO supercomputer at SU. Funded by the NSF and the College of Arts and Sciences, the cluster will be housed in the new Green Data Center on South Campus. Collaborating on the project are co-principal investigators Tomasz Skwarnicki, professor of physics; and Christopher Sedore, vice president for information technology/CIO. When it is completed this summer, the SU supercomputer will join LIGO computing centers at UW-M and the Albert Einstein Institute for Gravitational Physics in Germany and the LIGO Laboratory's main computing center to provide resources for LIGO scientists worldwide.

The SU group is also taking the lead on projects to improve the gravitational-wave search software for Advanced LIGO and develop new technologies that will increase the sensitivity of LIGO instruments beyond what is currently possible. In addition to Saulson and Brown, the group includes physics professor Stefan Ballmer, who is building a mini-LIGO prototype at SU to explore new ways to enhance the sensitivity of LIGO instruments (see page 40). Computing specialist Peter Couvares, two postdoctoral researchers, seven graduate students, and two undergraduates

Physics professor Duncan Brown (center) and Christopher Sedore, vice president for information technology/CIO, discuss the supercomputer they are building at the Green Data Center on South Campus. Almir Alemic '14, a physics major, checks some cables.

Top left: Model of supermassive black hole at the center of the Milky Way galaxy developed by using data from NASA's Chandra X-ray Observatory.
Image courtesy of NASA

Top right: Scientists used a NASA supercomputer to create a three-dimensional simulation of merging black holes producing gravitational waves. This image models a phase of the merger.
Image by Henze/NASA

Photo by Steve Sartori

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Peter Saulson (right), the Martin A. Pomerantz '37 Professor of Physics, watches postdoctoral research associate Joshua Smith '02 demonstrate an apparatus he developed to measure how light scatters off the surface of high-quality mirrors, an important issue in making mirrors good enough to use in LIGO. Smith is now a faculty member at California State University, Fullerton, where he heads a gravitational-wave group that is a member of the LIGO Scientific Collaboration.

are also involved in SU's LIGO research group.

At the core of LIGO technology is the laser interferometer, which uses a beam of light and a photodetector to sense gravitational waves. Specifically, it measures the distance light travels in a vacuum between suspended mirrors located at either end of four-kilometer-long, L-shaped "arms." Gravitational waves and other vibrations and noise cause the mirrors to move a tiny bit—less than the diameter of a proton. The movement changes the distance light travels between the mirrors, which is measured by the photodetector and converted into an electrical signal—the musical notes of the cosmos.

One noise that plagued the initial LIGO instruments was a barely perceptible jitter in the glass mirrors caused by friction from the movement of silicon and oxygen atoms in the glass. The jitter was invisible to the naked eye—and most instruments—but loud enough to cover the sound of gravitational waves. "We needed to significantly reduce this noise, but the only trick we knew was to replace the glass with sapphire, which has very low friction," Saulson says. "I spent my first 10 years at SU trying to learn whether there was any way you could buy, treat, or hold a form of glass that would have the friction level of sapphire yet retain the properties we required—and we found it."

Saulson's team discovered an extremely pure form of silicon dioxide that has a very low internal friction. It was a significant accomplishment that required the team to develop a way to measure internal friction before they could begin to analyze different types of glass. Saulson has now moved to new areas of LIGO research, one of which is to improve the gravitational-wave search software for Advanced LIGO. "As cool as the glass stuff is, I really want to find gravitational waves in the data," Saulson says. "SU is one of the leading institutions in the country in LIGO. We should all take pride in our role in building very important pieces of the LIGO effort." «

THE **NEXT STEP:** BLOCKING the CLANGS and BANGS

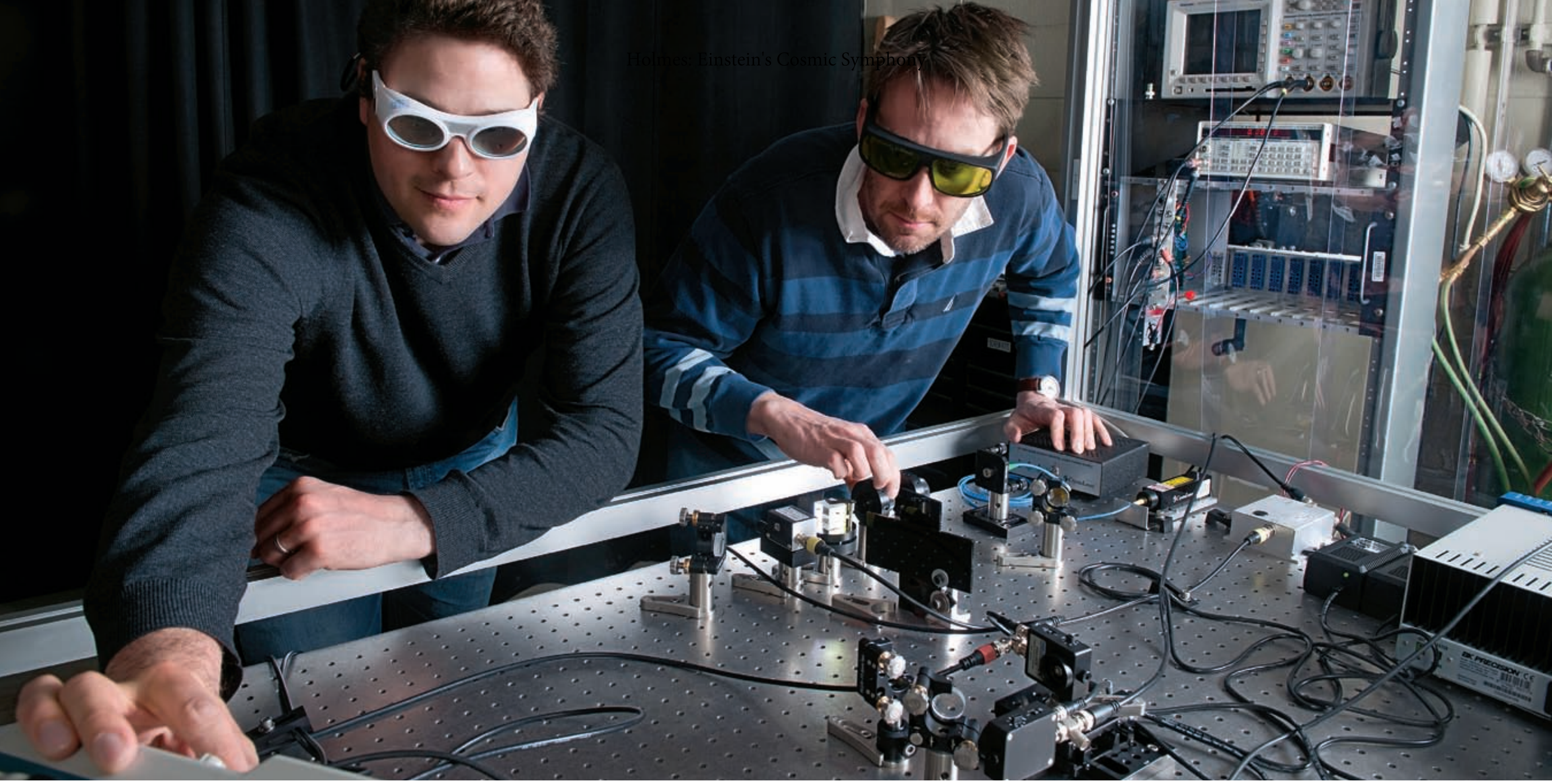
ALMOST A CENTURY AGO, Albert Einstein predicted that colliding pairs of stars or black holes (binary systems) release energy-carrying gravitational waves that travel millions of light years across the universe. Peter Saulson seeks to be among the first to hear those waves—dubbed Einstein's Messengers. To do that, he and his research team must devise better ways to muffle external noise. "We learned a lot during the eight years initial LIGO operated," says Saulson, the Martin A. Pomerantz '37 Professor of Physics in the College of Arts and Sciences, who has been involved with LIGO for more than 20 years. "We are drastically reducing the environmental and internal noise in Advanced LIGO instruments so that the primary thing we should hear is the universe."

In addition to improving the physical infrastructure, scientists are working to improve the computer algorithms (mathematical rules) used to search for the signals. It's an area of the LIGO consortium in which Saulson and his research team are playing a key role. "A lot of very good software was written for initial LIGO," Saulson says. "We are building on what we've learned to make the software quicker, smarter, and more resistant to instrumental noise."

Coincidently, SU physics professor Duncan Brown wrote much of the original search software as a doctoral student at the University of Wisconsin-Milwaukee. "Duncan drew me into the search for binary systems and into the area of data analysis," Saulson says. "He put up with my grumblings about the software. However, I don't think we've had many ideas to improve the software that Duncan has not already thought of. Nobody knows the system better than the person who created it."

Saulson's team, which includes doctoral candidate Matthew West, is tasked with writing algorithms that will make the software smart enough to disregard the clangs and bangs in the surrounding environment as well as the grunts and groans intrinsic to the instruments. Simultaneously, the new rules will enable the software to more precisely identify the predicted shapes of the signals coming from some of the most violent events in the universe. The improved software will also allow LIGO to see deeper into the universe. The team will test the new code against data collected during initial LIGO. "The beauty is that we are much better off than we were when the original code was written," Saulson says. "For initial LIGO, we could only invent fake data we thought would mimic environmental noise. But you can never faithfully invent all of the problems or imperfections that are found in real data. We now have lots of real LIGO data—with real imperfections—to help us fine-tune the search software."

Photo by Susan Kahn



Squeezing**LIGHT**

BEFORE ARRIVING AT SYRACUSE UNIVERSITY last fall, physics professor Stefan Ballmer worked at LIGO's Hanford Observatory where he listened for Einstein's heavenly symphony. He heard a cacophony of sounds: the electrical equivalent of whoops, clangs, and bangs emanating from noises as varied as water flowing over dams hundreds of miles away and trains vibrating their tracks to broken electronic circuits. But, the barely audible "hiss" he was listening for—a sound from the early universe akin to the "yopp" from the tiniest Who in Whoville—eluded him. "We got very good at distinguishing one vibration from another," Ballmer says. "You learned to hear things that went wrong with the gravitational-wave detector simply by noting a change in the vibrational noise."

Advanced LIGO, which will be installed in the two observatories over the next three years, is designed to overcome the limitations of the first-generation LIGO instrument. Advanced LIGO will filter out environmental noises, including minute noises generated by the detector itself, all of which can muffle the music of distant objects in the universe. It is as sensitive of an instrument as can be created with known technology. Ballmer, however, aims to explore the unknown. He is building a mini-LIGO in the basement of the Physics Building, which he will use to challenge the fundamental nature of light, and manipulate it to reduce its intrinsic vibrational noise.

Photos by Steve Sartori

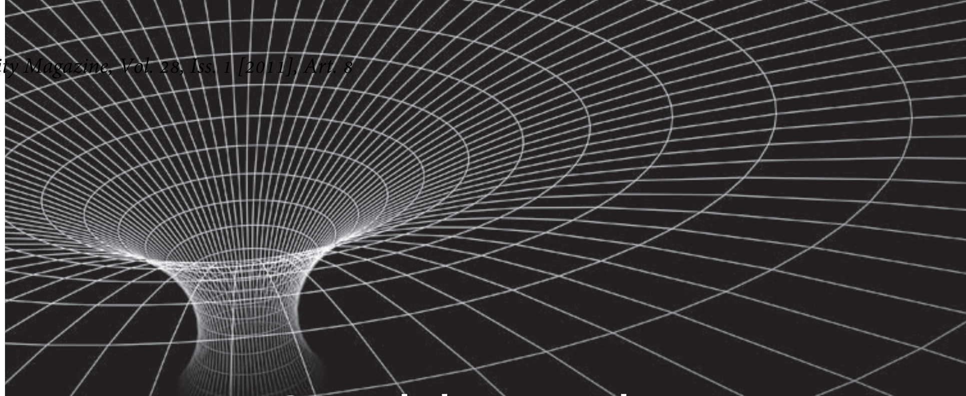
Physics professor Stefan Ballmer (at left in facing photo) and graduate student James Lough examine some of the equipment that Ballmer is using to construct a mini-LIGO in the Physics Building. Ballmer hopes the work will further enhance LIGO's sensitivity to vibrational noise.

The knowledge will help scientists further improve LIGO's sensitivity.

The traditional model of light is represented as an electromagnetic wave traveling across space and time. However, at the fundamental or quantum level, light is composed of tiny particles—individual photons that exhibit both wave-like and particle-like behavior. Laser light exploits the particle-like properties of light. Inside the LIGO interferometer, light is quantized, creating individual photons of light that bombard the mirrors and the photodetector like tiny pieces of hail pelting a window. The photons push the mirrors back a tiny bit (phase noise) and create a blip sound (shot noise) when they return to the photodetector, Ballmer says. These noises limit LIGO's ability to detect gravitational waves in ways that current technologies have not resolved. "It turns out this is not a fundamental problem," Ballmer says. "The trick is to produce a non-classical state of light in the interferometer. One way to do that is to squeeze the light so that the phase noise and the shot noise cancel each other out."

The mini-LIGO will be used to prove that a squeezed state of light can be produced and controlled. Ballmer will also explore ways to manipulate the tiny force that light exerts to automatically re-align the mirrors in the interferometer. The mirrors are currently kept in position through a system of sensors, tiny magnets, and electromagnetic fields.

The work has just begun. Ballmer estimates it will take up to three years just to build the scale LIGO. There are laser systems to be stabilized, mirror suspension systems to be designed and tested, sensors and circuit boards to be created, and software to be written. "We know the technology that exists," says Ballmer, who helped build the first LIGO instrument as a doctoral candidate at MIT. "We plan to go beyond that technology and help develop super Advanced LIGO." «



NINJA: Stealth Invaders

"If it is true that every theory must be based upon observed facts, it is equally true that facts cannot be observed without the guidance of some theory." —Auguste Comte, 1830

FRENCH PHILOSOPHER AUGUSTE Comte reasoned that scientific theory and experimentation are inextricable. This is especially true in gravitational-wave astronomy. Black holes are collapsed stars from which nothing—not even light—can escape. Until recent times, scientists could rely only on Albert Einstein's theory in their attempts to understand black holes.

Today, the LIGO Scientific Collaboration has technology for detecting gravitational waves—tiny ripples in the fabric of the universe emitted by black holes hundreds of thousands of light years away. But to find these tiny ripples hidden in the data collected by LIGO instruments, gravitational-wave astronomers must first understand what they are looking for.

Enter NINJA (Numerical INJection Analysis). NINJA is an international collaboration of more than 100 scientists whose goal is to link numerical relativity researchers (theorists) and LIGO gravitational-wave astronomers (experimentalists). "NINJA is the meeting ground for the two groups," says SU physics professor Duncan Brown, a NINJA collaborator. "After more than 30 years, both groups achieved their respective goals. It's now time for everyone to work together."

Six years ago, Frans Pretorius, a numerical relativity researcher at Caltech, cracked Einstein's equations to create the first computer simulation of two black holes locked in a death spiral, their collision, and the resulting gravitational waves. The task required very high-speed computers packed with computational power. "It was an incredibly complex, mathematical breakthrough," Brown says.

Today, scientists worldwide are developing simulations for different configurations of binary systems in motion and their gravitational-wave forms. Three years ago, NINJA hid the theorists' black hole simulations in fake LIGO gravitational-wave data the experimentalists created to test their detectors. "We challenged LIGO scientists to find the signals in the noise and use the information to describe the simulated black holes—mass, spin, orbital shapes," Brown says. "It's one thing to detect a gravitational wave, but can we really understand the physics we extract from the signal?"

The experiment worked and NINJA is repeating it—this time hiding new simulations in segments of real LIGO data collected between 2002 and 2010. "Einstein's equations predict how black holes behave, but we need experiments to fully understand his theory," Brown says. "We now have the capability to discover whether the theory matches the experiments. That's what astronomy and physics are all about."